Energy Efficient Smart Wireless Sensors Network

Prof. Daniela Dragomirescu
University of Toulouse, LAAS-CNRS
2013-2014 French Government Fellow of Churchill College, University of Cambridge

Contact: daniela@laas.fr
LAAS-CNRS laboratory

- 600 persons, 220 researchers
- Carnot institute - excellent relationship with the industry
- 1500 m² clean room
- Characterization center
- ADREAM platform for cyber-physical systems (from sensors to robots), autonomous in energy
Our project objective: develop a new platform to accommodate innovative CMOS sensors together with wireless systems to obtain energy efficient, reconfigurable WSN for many real-world applications.
Challenges – research fields

Real world, high scale deployment

Energy efficiency

Toward Zero Power = ultra low power consumption + energy harvesting

Low power sensors

Energy efficient wireless communication architectures

CMOS Integration (low cost, large area electronics)

Small size and flexible integration
Numerous industrial applications
Proposed design approach

- **Major driver: energy efficiency**
  - IR-UWB communications using nano-metric CMOS technology

- Application specific hardware $\rightarrow$ reconfigurability (MAC and physical layer)

- Include new Services such as:
  - Localization
  - Synchronization, time stamp
  - Safety, security

- System approach: Cross-layering between low network levels (PHY and MAC) and high network levels (routing)
Ultra Wide Band Impulse Radio Transmission for WSN
The advantages of IR-UWB

- Low level discontinue transmission
  - Low power transmission
  - Large frequency band
  - Very short pulse
  - Lower interference probability
  - Fine temporary resolution
    - Localization

- Low complexity circuits to be developed in CMOS technology → low cost, low power

- Challenges:
  - Channel estimation
  - Fast DAC/ADC
  - Reception synchronization

Patent
Applications requirements:
- Data rate
- E/R distance
- Frequencies used
- …

<table>
<thead>
<tr>
<th>Application</th>
<th>Structure Health Monitoring</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation on mean EIRP</td>
<td>-41.30</td>
<td>dbm/MHz</td>
</tr>
<tr>
<td>Distance</td>
<td>50.00</td>
<td>m</td>
</tr>
<tr>
<td>Data rate</td>
<td>1.00</td>
<td>Mbits/s</td>
</tr>
<tr>
<td>Low frequency</td>
<td>3.10</td>
<td>GHz</td>
</tr>
<tr>
<td>High frequency</td>
<td>6.85</td>
<td>GHz</td>
</tr>
<tr>
<td>Center frequency</td>
<td>4.98</td>
<td>GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>3.75</td>
<td>GHz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.27</td>
<td>ns</td>
</tr>
<tr>
<td>Time slot duration</td>
<td>1000.00</td>
<td>ns</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.0267</td>
<td>%</td>
</tr>
<tr>
<td>Mean EIRP</td>
<td>-5.56</td>
<td>dbm</td>
</tr>
<tr>
<td>Max. EIRP</td>
<td>30.18</td>
<td>dbm</td>
</tr>
<tr>
<td>Tx antenna Gain</td>
<td>3.00</td>
<td>dB</td>
</tr>
<tr>
<td>Rx antenna Gain</td>
<td>10.00</td>
<td>dB</td>
</tr>
<tr>
<td>Power max. feed to antenna</td>
<td>522.47</td>
<td>mW</td>
</tr>
<tr>
<td>Channel path loss</td>
<td>86.11</td>
<td>dB</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>1.38E-23</td>
<td>J/K</td>
</tr>
<tr>
<td>Temperature</td>
<td>293.50</td>
<td>K</td>
</tr>
<tr>
<td>Thermal Noise density</td>
<td>-175.31</td>
<td>dbm/MHz</td>
</tr>
<tr>
<td>Available Eb/N0</td>
<td>69.38</td>
<td>dB</td>
</tr>
<tr>
<td>Supported delay spread</td>
<td>999.73</td>
<td>ns</td>
</tr>
</tbody>
</table>

From system to hardware

System Architecture Design

Wireless Sensor Network Context
Application Needs

System Modeling
Simulation & Validation

FPGA Implementation
ASIC Implementation

HARDWARE

Test & Evaluation

MATLAB

Specifications
Matlab Language

IR-UWB Reconfigurable Transceiver

Link Budget

- BER versus Eb/N0 - synchronization error
- Data rate – spectrum occupation

- Yes
- No

Link Budget

- Application Needs
- Structure Health Monitoring
- Units

- Data rate
- E/R distance
- Frequencies used
- …
- IR-UWB multi user emitter and receiver
- IR-UWB receiver with localization function
- IR-UWB reconfigurable transceiver in modulation, pulse duration, spectral occupation, data rate and user code
- IR-UWB reconfigurable transceiver at 120Mb/s – state of art: 50Mb/s (Electronics Letters, March 2010)
Measurements of first UWB IR emitter performances

Measured results:

- Data rate: 8 to 375 Mbits/s
- $T_p$: 20 ns to 720 ps
- Consumption: 60 $\mu$W to 515 $\mu$W
- FOM: 7.23 to 1.4 pJ/bit
Low power ASICs - emitter/receiver
IR-UWB

- UWB-IR emitter – CMOS 65 nm STMicro. technology. Low complexity digital design: fast and reliable
- 1st emitter prototype: without DAC, 1 bit output, OOK modulation
- 2nd emitter prototype: reconfigurability in data rate (up to 1 Gbps), modulation, impulse form, impulse duration.
- 3rd emitter/receiver prototype: with DAC/ADC and MAC layer

Simulated power consumption < 40 mW for a data rate up to 500Mbits/s
MAC layer and clock synchronisation for IR-UWB
Context:
- Static cluster tree network
- No mobile nodes
- Clock synchronization needed

Solution:
- TDMA
- WiDeCS Sync Protocol – LAAS-CNRS solution
Cross-layer design
WiDeCS synchronization

Goals:
- Compensate clock offset
- Estimate transmission latency and compensate its variations

Solution:
- 2 way ranging
- Periodic update
- Timestamp 1st effective bit instead of 1st bit of preamble

\[
\Delta t_{\text{clk}} = \frac{(\Delta t_i + \delta t_m) - (\delta t_i + \Delta t_m)}{2}
\]

\[
\Delta t_{\text{clk}} = \frac{\Theta_i - (\delta t_i + \Delta t_m)}{2}
\]
Wireless communicating node FPGA prototype

- RedRapids boards with Virtex 4 and DAC/ADC
- IR-UWB
- TDMA MAC layer
- WiDeCs synchronization protocol
FPGA prototype with MAC layer and clock synchronization using UWB transmission

- Scope measurement prove clock synchronization → good accuracy in ToF measurements

See demo for clock synchronization and for aircraft in flight test at http://www.laas.fr/~daniela → News (April 2012)
ASIC prototype: MAC layer, clock synchronization and IR-UWB transceiver

- 1 mm² chip with
  - PHY layer: IR-UWB BPSK transceiver
  - TDMA MAC layer
  - Clock synchronization
  - Fast ADC/DAC
  - Mixte SoC
  - Build to interface with RF front-end
Test platform

SoC Chips
Measurements results

$P_c = 50$ mW

Max data rate: 500Mbps

Energy/bit: 100 pJ/bit (best case)

Clock synchronization precision $\sim 1$ ns
SoC IR-UWB @ 60GHz

60GHz communications enabled by nano-metric CMOS technology

- Short transmission range and high directivity → Low interferences between nodes
- High number of communicating nodes in a small area
- CMOS 65 nm technology → Low power consumption, Low cost
SoC IR-UWB @ 60GHz

Baseband (BB)

Digital BB

Data out

Data in

Receiver Front-End

Transmitter Front-End

Phased array

RF MEMS

Phase shifters

PA

Antenna Array

Nano-Sensors

Integrated antenna

Flexible substrate

Transceiver

Antenna Array

RF MEMS

Phase shifters

PA

RFIC (CMOS)

Baseband/MAC
Architecture of 60GHz Front-end

Transmitter

- Direct Conversion Topology
- Implementation in 65 nm CMOS

Channel

Receiver

Small size
Low power consumption
Ultra low power 60GHz Transmitter

Performances of the chip:
- **Bias Voltage = 1.2 V**
- **Power consumption = 53 mW**
- Conversion gain > 5dB @60GHz
- Bandwidth ~10 GHz
- Size: 0.6 mm²
Performances of the system

- Single tone bandwidth ~ 15 GHz
Low power 60GHz CMOS 65 nm receiver

Performances of the chip:
- Bias Voltage = 1.2 V
- Power consumption = 43 mW
- Max conversion gain ~ 30dB
- Bandwidth ~ 5 GHz
- Size: 0.55 mm²
System integration for wireless sensor communicating node
Flexible substrate integration

- **Technological choice:** material selection, technological process set-up
- **60GHz electrical interconnections:** Design and fabrication of test structures
Flip Chip Characterization

Probe station

Impedence-meter

Structures under test
Flip Chip Characterization

- Bump ~ 15 mΩ
- RF loses < 1 dB
New 3D packaging: complete communicating node integration on flexible substrate.

MAC layer and IR-UWB PHY layer with DAC/ADC ($\approx 50$ mW)

60GHz CMOS emitter ($\approx 53$ mW today in our design)

MAC layer and IR-UWB PHY layer with DAC/ADC ($\approx 50$ mW)

Major advantage of flexible substrate integration: facility to deploy the WSN nodes for any application
Wireless Sensor Network solution proposed:

- IR-UWB reconfigurable emitter and receiver developed on FPGA
- Impulse radio UWB transceiver on ASIC developed → very low power
- Cross-layering MAC –PHY
- Clock Synchronization
- 60GHz architectures developed on ASIC in CMOS 65nm technology
- SoC Architectures - flexible substrate integration
- WSN simulator using UWB-impulse radio developed → determine the best network topology for one application
Thank you for your attention!